Mon. Not. R. Astron. Soc. **000**, 1–10 (2005) Printed 4 February 2008 (MN LaTeX style file v2.2)

New H-band Galaxy Number Counts: A Large Local Hole in the Galaxy Distribution?

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Accepted 2005. Received 2005; in original form 2005

ABSTRACT

We examine H-band number counts determined using new photometry over two fields with a combined solid angle of 0.30 deg^2 to $H \approx 19$, as well as bright data ($H \leqslant 14$) from the 2 Micron All Sky Survey (2MASS). First, we examine the bright number counts from 2MASS extracted for the ≈4000 deg^2 APM survey area situated around the southern galactic pole. We find a deficiency of ≈25 per cent at $H = 13$ with respect to homogeneous predictions, in line with previous results in the B-band and K_s-band. In addition we examine the bright counts extracted for $|b| > 20°$ (covering ≈27 000 deg^2); we find a relatively constant deficit in the counts of ≈15-20 per cent to $H = 14$. We investigate various possible causes for these results; namely, errors in the model normalisation, unexpected luminosity evolution (at low and high redshifts), errors in the photometry, incompleteness and large-scale structure. In order to address the issue of the model normalisation, we examine the number counts determined for the new faint photometry presented in this work and also for faint data ($H \lesssim 20$) covering 0.39 deg^2 from the Las Campanas Infra Red Survey (LCIRS). In each case a zeropoint is chosen to match that of the 2MASS photometry at bright magnitudes using several hundred matched point sources in each case. We find a large offset between 2MASS and the LCIRS data of 0.28±0.01 magnitudes. Applying a consistent zeropoint, the faint data, covering a combined solid angle of 0.69 deg^2, is in good agreement with the homogeneous prediction used previously, with a best fit normalisation a factor of $1.095^{+0.035}_{-0.034}$ higher. We examine possible effects arising from unexpected galaxy evolution and photometric errors and find no evidence for a significant contribution from either. However, incompleteness in the 2MASS catalogue (< 10 per cent) and in the faint data (likely to be at the few per cent level) may have a significant contribution. Addressing the contribution from large-scale structure, we estimate the cosmic variance in the bright counts over the APM survey area and for $|b| > 20°$ expected in a ΛCDM cosmology using 27 mock 2MASS catalogues constructed from the ΛCDM Hubble Volume simulation. Accounting for the model normalisation uncertainty and taking an upper limit for the effect arising from incompleteness, the APM survey area bright counts are in line with a rare fluctuation in the local galaxy distribution of $\approx 2.5\sigma$. However, the $|b| > 20°$ counts represent a 4.0σ fluctuation, and imply a local hole which extends over the entire local galaxy distribution and is at odds with ΛCDM. The increase in faint near infrared data from the UK Infrared Deep Sky Survey (UKIDSS) should help to resolve this issue.

Key words: galaxies: photometry - cosmology: observations - large-scale structure of the Universe - infrared: galaxies

1 INTRODUCTION

A recurring problem arising from the study of bright galaxy number counts has been the measured deficiency of galaxies around the southern galactic pole. This was first examined in detail by Shanks (1990) and subsequently by the APM galaxy survey (Maddox et al. 1990a), which observed a large deficit in the number counts (≈50 per cent at $B = 16$, ≈30 per cent at $B = 17$) over a ≈4000 deg^2 solid angle. If this anomaly was due solely to features in the galaxy distri-

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bution, this would be at odds with recent measurements of the variance of local galaxy density fluctuations (e.g. Hawkins et al. 2003; Frith et al. 2005b; Cole et al. 2005) or the expected linear growth of density inhomogeneities at large scales.

Maddox et al. (1990b) examined possible causes of this deficiency. From redshift survey results over the APM survey area (Loveday et al. 1992), it was argued that a weak local under-density contributed to the observed deficiency at the $\lesssim 10$ per cent level at $B \approx 17$. Instead, Maddox et al. (1990b) suggested that strong low redshift galaxy evolution was the dominant contribution. This phenomenon has also been suggested as a possible explanation for large deficiencies in the Sloan Digital Sky Survey (SDSS; Loveday 2004), although models without such strong low redshift evolution provide predictions consistent with observed number redshift distributions (e.g. Broadhurst et al. 1988; Colless et al. 1990; Hawkins et al. 2003). In contrast, Shanks (1990) argued that evolution could not account for the observed slope and that large-scale structure was the principal cause of the deficiency in the counts.

However, another possible contribution to the low counts might be errors in the APM photometry. Comparing the photographic APM photometry with B-band CCD data, Metcalfe et al. (1995) detected a small residual scale error in the APM survey zeropoints for $B \gtrsim 17$. Correcting for this offset, the counts were now in good agreement with homogeneous predictions at faint magnitudes ($B \gtrsim 17.5$); however, the problematic deficiency at brighter magnitudes remained. More recently, Busswell et al. (2004) used B-band CCD data over ≈ 337 deg^2 within the APM survey area to provide the most accurate comparison to date with a sample of the APM survey photometry. The photometric zeropoint of this CCD data was in excellent agreement with the Millennium Galaxy Catalogue (Driver 2003) and the Sloan Digital Sky Survey Early Data Release (Yasuda et al. 2001). However, a comparison with the APM photometry suggested a large offset of 0.31 magnitudes for $B < 17.35$. Applying this to the APM survey counts, a deficiency of ≈ 25 per cent remained at $B = 16$; Busswell et al. (2004) determined that such a deficiency in the local galaxy distribution would still be at odds with a ΛCDM form to the galaxy correlation function and power spectrum at large scales.

In order to examine this issue independently, bright number counts have also been examined in the near infrared (Frith et al. 2003, 2004, 2005a). These wavelengths are particularly useful for such analysis as the number count predictions are fairly insensitive to the evolutionary model or the assumed cosmology at bright magnitudes (see Fig. 1); current observations are in remarkable agreement with predictions in the K-band to $K \approx 23$ for example (McCracken et al. 2000) In particular, Frith et al. (2005a) examined K_s-band number counts selected from the 2 Micron All Sky Survey (2MASS; Jarrett 2004). First, the counts over the APM survey area were determined; a similar deficiency was observed to the APM survey counts (with the zeropoint offset determined by Busswell et al. (2004) applied), with a ≈ 25 per cent deficit at $K_s = 12$ compared to the no evolution model of Metcalfe et al. (2001). Using a ΛCDM form for the angular correlation function at large scales and assuming the observed counts were solely due to features in the local galaxy distribution, the observed counts represented a 5σ fluctuation. However, this result was complicated by the fact that the 2MASS K_s-band number counts for almost the entire survey ($|b| > 20°$, covering $\approx 27\,000$ deg^2) were also low, with a constant deficiency of ≈ 20 per cent between $K_s = 10$ and $K_s = 13.5$.

Did this surprising result perhaps indicate that the K_s-band Metcalfe et al. (2001) model normalisation was too high? Or, as suggested previously, could low redshift luminosity evolution significantly affect the bright counts? These issues were also addressed by Frith et al. (2005a): First, the Metcalfe et al. (2001) model was compared with faint K-band data collated from the literature. Fitting in the magnitude range $14 < K < 18$ it was found that the best fit model normalisation was slightly too high, although not significantly (this magnitude range was used so as to avoid fluctuations in the counts arising from large-scale structure at bright magnitudes and significant effects from galaxy evolution at the faint end). Accounting for the normalisation uncertainty (of ± 6 per cent) the observed deficiency in the K_s-band counts over the APM survey area still represented a $\approx 3\sigma$ fluctuation. Second, the issue of low redshift luminosity evolution was also addressed: 2MASS galaxies below $K_s = 13.5$ were matched with the Northern and Southern areas of the 2dF Galaxy Redshift Survey (2dGRS; Colless et al. 2001). The resulting $n(z)$, covering > 1000 deg^2 in total, was consistent with the no evolution model of Metcalfe et al. (2001). In addition, these K_s-band redshift distributions were used to form predictions for the number counts over the Northern and Southern 2dFGRS areas respectively. This was done by multiplying the luminosity function parameter ϕ^* (which governs the model normalisation) used in the Metcalfe et al. (2001) model by the relative density observed in the K_s-band $n(z)$ as a function of redshift. These 'variable ϕ^* models' were then compared with 2MASS counts extracted for the 2dFGRS areas in order to determine whether the observed counts were consistent with being due solely to features in the local galaxy distribution; the variable ϕ^* models were in good agreement with the number counts, indicating that low redshift luminosity evolution is unlikely to have a significant impact on the observed deficiency in the counts, in the K_s-band at least.

In this paper we aim to address the issue of low, bright number counts in the near infrared H-band. In particular we wish to address a drawback to the K_s-band analysis of Frith et al. (2005a) - the issue of the number count model normalisation; while the K_s-band model used was compared with faint data and was found to be in good agreement, the level to which systematic effects, arising perhaps via zeropoint offsets between the bright and faint data or cosmic variance in the faint data, might affect the conclusions were uncertain. We address this issue in the H-band using new faint data covering 0.3 deg^2 to $H = 18$, calibrated to match the 2MASS zeropoint. In section 2, we first verify that the H-band counts provide number counts over the APM survey area which are consistent with the previous results in the B and K_s-bands (Busswell et al. 2004; Frith et al. 2005a), and that the form of the counts is not significantly affected by low redshift luminosity evolution through comparisons with the variable ϕ^* models described above. In section 3, we provide details of the data reduction of the new faint H-band photometry. The associated counts are presented in section 4. In section 5 we discuss possible systematics affecting the

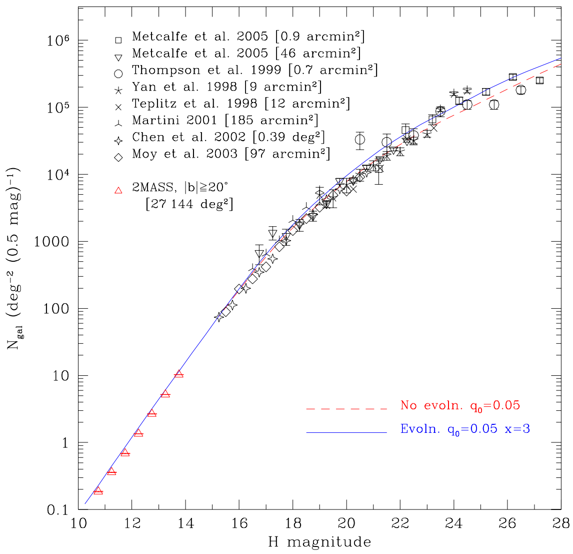

Figure 1. H-band galaxy number counts collated from the literature. The dashed and solid lines indicate the no evolution and pure luminosity evolution predictions respectively, described in section 2. We also show bright H-band counts extracted from the 2MASS extended source catalogue for $|b| > 20°$. For each dataset, we indicate the associated observed solid angle in square brackets.

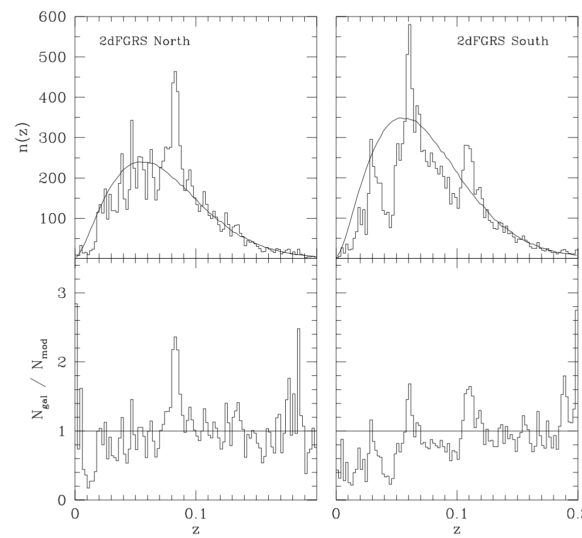

Figure 2. Number redshift histograms for 11 501 and 13 687 H <14 2MASS galaxies matched with the 446 deg^2 Northern (left hand) and 647 deg^2 Southern (right hand panels) 2dFGRS declination strips respectively. In each case the solid lines indicate the pure luminosity evolution prediction for a homogeneous distribution described in section 2 normalised by the respective solid angles. We also indicate the relative density in the lower panels, dividing the observed $n(z)$ by the homogeneous prediction.

bright number counts including the model normalisation and incompleteness. The conclusions follow in sections 6.

2 BRIGHT H-BAND COUNTS FROM 2MASS

We wish to examine the form of bright number counts in the H-band in order to verify that the counts over the APM survey area (≈4000 deg^2 around the southern galactic pole) are comparable to those measured previously in the optical B-band and near infrared K_s-band (Busswell et al. 2004; Frith et al. 2005a). The near infrared has the advantage of being sensitive to the underlying stellar mass and is much less affected by recent star formation history than optical wavelengths. For this reason, number count predictions in the near infrared are insensitive to the evolutionary model at bright magnitudes. In Fig. 1 we show faint H-band data collated from the literature along with bright counts extracted from 2MASS over ≈27 000 deg^2. The 2MASS magnitudes are determined via the 2MASS H-band extrapolated magnitude; this form of magnitude estimator has previously been shown to be an excellent estimate of the total flux in the K_s-band (Frith et al. 2005b,c) through comparison with the total magnitude estimates of Jones et al. (2004) and the K-band photometry of Loveday (2000). Throughout this paper we use 2MASS H-band counts determined via this magnitude estimator. We also show two models in Fig. 1 corresponding to homogeneous predictions assuming no evolution and pure luminosity evolution models. These are constructed from the H-band luminosity function parameters listed in Metcalfe et al. (2005) and the $K + E$-corrections of Bruzual & Charlot (1993). At bright magnitudes the two are indistinguishable; only at $H \gtrsim 18$ do the model predictions begin to separate. The faint data is in good agreement with both the no evolution and pure luminosity evolution predictions to H ≈26.

Before examining the H-band counts over the APM survey area, we first verify that the bright counts are consistent with relatively insignificant levels of low redshift luminosity evolution in the manner carried out by Frith et al. (2005a) for the K_s-band counts. In the upper panels of Fig. 2 we show H-band $n(z)$ to the 2MASS limiting magnitude of $H = 14$, determined through matched 2MASS and 2dFGRS galaxies over the 2dFGRS Northern (left hand) and Southern (right hand panels) declination strips (see Frith et al. (2005a) for further details of the matching technique). The solid lines indicate the expected homogeneous distribution constructed from the pure luminosity evolution predictions of Metcalfe et al. (2005) (there is no discernible difference between this and the no evolution prediction). In the lower panels we divide through by this prediction; these panels show the relative density as a function of redshift. The observed $n(z)$ are consistent with the expected trends, with relatively homogeneous distributions beyond $z = 0.1$ (1 per cent and 8 per cent over-dense in the North and South respectively for $0.1 \leqslant z \leqslant 0.2$). For this reason, Fig. 2 suggests that the level of luminosity evolution is relatively insignificant at low redshifts in the H-band; strong luminosity evolution produces an extended tail in the predicted $n(z)$ which is not observed in the data.

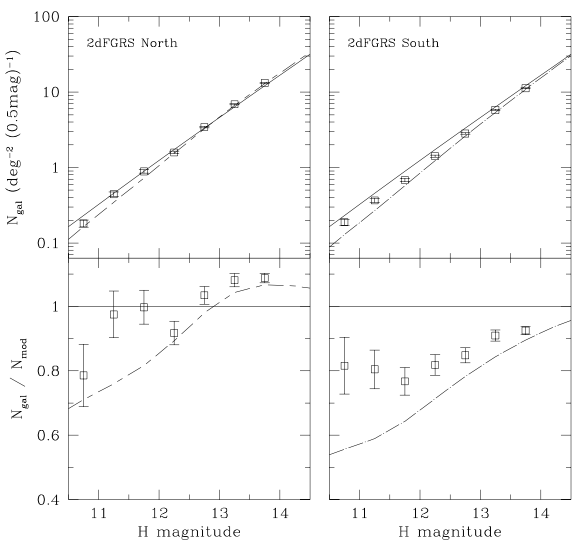

Figure 3. H-band 2MASS galaxy number counts extracted from the Northern (left hand) and Southern (right hand) 2dFGRS declination strips. The solid line indicates the homogeneous pure luminosity evolution prediction described in section 2 (this and the no evolution prediction are indistinguishable at these magnitudes). The dashed and dot-dashed lines indicate the variable ϕ^* models for the Northern and Southern 2dFGRS strips respectively; these indicate the expected number counts given the observed $n(z)$ (Fig. 2). In the lower panels we divide through by the homogeneous prediction. In each case the errorbars indicate the Poisson uncertainty in each bin.

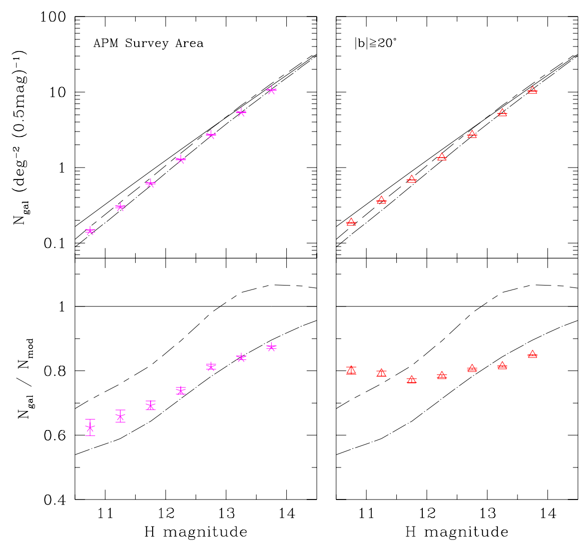

Figure 4. H-band 2MASS galaxy number counts extracted for the APM survey area ($\approx$4 000 deg^2) and for $|b| > 20^\circ$ ($\approx$27 000 deg^2), shown in the left and right hand panels respectively. As in Fig 2, we show the homogeneous pure luminosity prediction (solid line), and the Northern (dashed) and Southern (dot-dashed) variable ϕ^* models, indicating the expected number counts for the redshift distributions shown in Fig. 2. As before, in the lower panels we divide through by the homogeneous prediction. In each case the errorbars indicate the Poisson uncertainty in each bin.

As a further check against strong low redshift luminosity evolution, we can use the observed $n(z)$ to predict the expected H-band number counts over the 2dFGRS declination strips. This technique is described in detail in Frith et al. (2003, 2005a). To recap, we use the observed density (Fig. 2, lower panels), to vary the luminosity function normalisation (ϕ^*) used in the Metcalfe et al. (2005) model as a function of redshift (for $z \leqslant 0.2$). We show these 'variable ϕ^* models' along with the 2MASS H-band counts extracted for the 2dFGRS strips in Fig. 3. In each case, the upper panels indicate the number count on a logarithmic scale; in the lower panels we divide through by the homogeneous prediction. In both the Northern and Southern 2dFGRS areas, the counts are in good agreement with the expected trend, defined by the corresponding variable ϕ^* model. This indicates that real features in the local galaxy distribution are the dominant factor in the form of the observed H-band number counts, and that strong low redshift luminosity evolution is unlikely to have a significant role in any under-density observed in the APM survey area.

We are now in a position to examine the number counts over the APM survey area. In Fig. 4 we show counts extracted for the $\approx$4000 deg^2 field along with the homogeneous and the Northern and Southern 2dFGRS variable ϕ^* models shown in Fig. 2. The form of the counts is in good agreement with the B (Busswell et al. 2004) and K_s-band (Frith et al. 2005a) bright number counts measured over the APM survey area, with a deficiency of $\approx$25 per cent below $H = 13$. In addition, the form of the counts is similar to that of the counts extracted from the 2dFGRS Southern declination strip and the corresponding variable ϕ^* model (this is also observed in the B and K_s-band); this perhaps indicates that the form of the local galaxy distribution in the $\approx$600 deg^2 2dFGRS Southern declination strip is similar to that of the much larger APM survey area, with an under-density of $\approx$25 per cent to z =0.1. However, the 2MASS H-band counts over almost the entire survey ($|b| > 20^\circ$, $\approx$27 000 deg^2) are also deficient (as are the K_s-band counts), with a relatively constant deficit of $\approx$15-20 per cent to $H = 14$ (Fig 3, right hand panels).

The low $|b| > 20^\circ$ counts raise the question as to whether systematic effects are significant, or whether these counts are due to real features in the local galaxy distribution, as suggested by the agreement between the variable ϕ^* models and corresponding counts in Fig. 3. If the latter is true, then the size of the local hole would not only be much larger than previously suggested but would also represent an even more significant departure from the form of clustering at large scales expected in a ΛCDM cosmology. In the following two sections we address a possible source of systematic error using new faint H-band photometry - the model normalisation. Other possible causes for the low counts are also discussed in section 5.

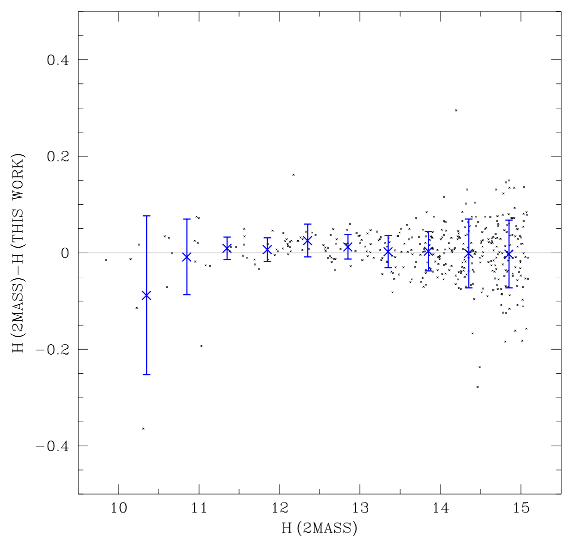

Figure 5. Here we examine the uncertainty in our photometric calibration with 2MASS. The H-band magnitudes determined by 2MASS and the residual with our photometry are indicated for 393 point sources below $H = 15.1$. The large datapoints indicate the mean offset and *rms* dispersion as a function of magnitude. The zeropoint used is indicated by the solid line and is accurate to ± 0.01 magnitudes at 1σ confidence.

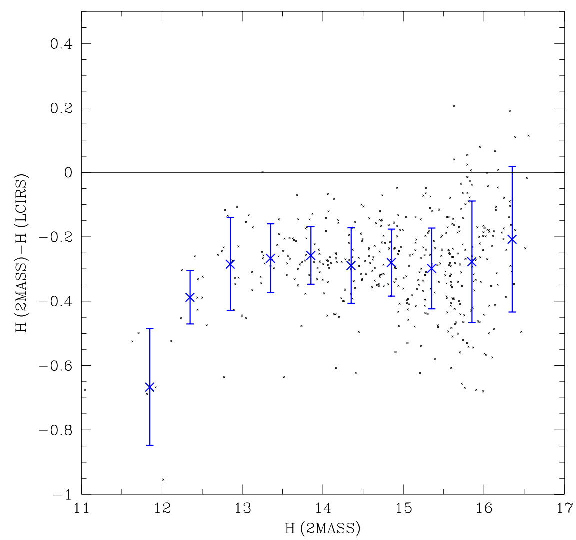

Figure 6. We compare the H-band photometry of the LCIRS (Chen et al. 2002) with 2MASS using 438 points sources. As in Fig. 5, the large datapoints indicate the mean offset and *rms* dispersion as a function of magnitude. The mean offset is -0.28$\pm$0.01 magnitudes at 1σ confidence. The zeropoint used in the new data presented in this work is indicated by the solid line.

3 NEW FAINT H-BAND DATA

3.1 Observations & data reduction

Our data were taken during a three night observing run in September 2004 at the f/3.5 prime focus of the Calar Alto 3.5m telescope in the Sierra de Los Filabres in Andalucia, southern Spain. The Ω-2000 infra-red camera contains a 2048×2048 pixel HAWAII-2 Rockwell detector array, with 18.5μm pixels, giving a scale of 0.45"/pixel at the prime focus. All observations were taken with the H-band filter. Poor weather meant that only just over one night's worth of data were usable, and even then conditions were not photometric.

Our primary objective was to image the William Herschel Deep Field as deeply as possible (the results of which are presented in a forthcoming paper), but time was available at the start of each night to image several 'random' fields for 15 minutes each. These were composed of individual 3 second exposures, stacked in batches of 10 before readout. A dithering pattern on the sky with a shift up to $\pm$25" around the nominal centre was adopted.

Data reduction was complicated by the fact that both the dome and twilight sky flat fields appeared to have a complicated out-of-focus pattern of the optical train imprinted upon them (probably an image of the top end of the telescope). This appeared (in reverse) in the science data if these frames where used for flat-fielding. We therefore constructed a master flat field by medianing together all the science frames from a particular night. This was then used to flat-field all the data. Then, individual running medians were constructed from batches of 10 or so temporally adjacent frames, and these were subtracted from each frame to produce a flat, background subtracted image. These were then aligned and stacked together (with sigma clipping to remove hot pixels).

3.2 Calibration

Photometric calibration of the H-band images is obtained through comparison with the 2MASS point source catalogue. Fig. 5 shows the 2MASS magnitudes compared with our data for 393 matched point sources over the Calar Alto field and the William Herschel Deep Field. The zeropoint of our data is chosen to match that of the 2MASS objects and is accurate to $\pm$0.01 magnitudes. The large datapoints and errorbars indicate the mean offset and *rms* dispersion as a function of magnitude. When comparing this data to the 2MASS number counts at bright magnitudes it is important to note that the 2MASS point source catalogue includes a maximum bias in the photometric zeropoint of <2 per cent around the sky (see the 2MASS website).

3.3 Star/Galaxy separation

We use the Sextractor software to separate objects below $H = 18$; for this magnitude limit, the associated STAR_CLASS parameter provides a reliable indicator of stars and galaxies. We identify 30.0 per cent as galaxies (CLASS_STAR<0.1), 58.9 per cent as stars (CLASS_STAR>0.9), leaving 11.1 per cent as unclassified.

H	$N_{CA\ field}$	N_{WHDF}	N_{HDFS}	N_{CDFS}	N_{tot} ($\deg^{-2}$ (0.5mag)$^{-1}$)	N_{mod} ($\deg^{-2}$ (0.5mag)$^{-1}$)
14.25	10	4	6	8	40.8	23.0
14.75	17	5	12	8	61.1	43.5
15.25	21	9	23	23	110	81.9
15.75	41	14	31	43	188	153
16.25	55	15	77	51	288	280
16.75	133	39	163	73	594	500
17.25	217	58	238	135	943	861
17.75	283	77	337	256	1.44×10^3	1.43×10^3

Table 1. The raw number counts per half magnitude are shown for the new H-band data described in section 3 - the CA field (0.27 deg^2) and WHDF (0.06 deg^2) in columns 2 and 3. In addition, we show the counts for the LCIRS fields, the HDFS (0.24 deg^2) and CDFS (0.16 deg^2) in columns 4 and 5, applying the zeropoint offset determined with respect to 2MASS in section 4.1. The total number count per deg^2 for all fields combined (0.69 deg^2) is shown in column 6 along with the homogeneous pure luminosity evolution prediction of Metcalfe et al. (2005) in column 7. The faintest magnitude bin for the CA field is slightly smaller (0.21 deg^2) than at brighter magnitudes; the combined solid angle for the faintest bin in column 6 is therefore 0.66 deg^2.

4 FAINT H-BAND COUNTS

4.1 Comparison with the LCIRS

Before determining number counts for the new H-band data described in section 3, we first examine the photometry of the Las Campanas Infra-Red Survey (LCIRS; Chen et al. 2002). The published data covers 847 arcmin^2 in the Hubble Deep Field South (HDFS) and 561 arcmin^2 in the Chandra Deep Field South (CDFS); the combined solid angle (0.39 deg^2) represents the largest H-band dataset for $14 \lesssim H \lesssim 20$. The associated number counts are ≈15 per cent below the homogeneous Metcalfe et al. (2005) predictions at $H = 18$ (see Fig. 1). This is significant, as if the model normalisation was altered to fit, the deficiency in the 2MASS counts at bright magnitudes (Fig. 3) would become much less severe. However, various other surveys show higher counts, although over much smaller solid angles. With the LCIRS data in particular therefore, it is vital to ensure that the photometric zeropoint is consistent with the 2MASS data at bright magnitudes.

In Fig. 6 we compare the LCIRS and 2MASS H-band photometry for 438 points sources matched over the HDFS and CDFS fields. There appears to be a large offset which is approximately constant for $K > 12$. Using point sources matched at all magnitudes, we determine a mean offset of -0.28±0.01 magnitudes; this is robust to changes in the magnitude range and is consistent over both the HDFS and CDFS fields.

4.2 New H-band counts

In Fig. 7 we show counts determined for the new H-band data described in section 3, the 0.27 deg^2 CA field and the 0.06 deg^2 WHDF (see also table 1). Both sets of counts are in excellent agreement with the pure luminosity evolution and no evolution homogeneous predictions of Metcalfe et al. (2005). In addition we show LCIRS counts determined in the 0.24 deg^2 HDFS and 0.16 deg^2 CDFS, applying the 0.28 magnitude zeropoint offset determined with respect to 2MASS in section 4.1. The associated counts are also in excellent agreement with the Metcalfe et al. (2005) models at all magnitudes.

In Fig. 8, we show counts determined from our data and the LCIRS combined, with a consistent zeropoint applied as in Fig. 7. We estimate the uncertainty arising from cosmic variance using field-to-field errors, weighted by the solid angle of each field. These combined counts are in good agreement with the Metcalfe et al. (2005) models, particularly at fainter magnitudes where the dispersion in the counts arising from cosmic variance appears to be small. We perform least squares fits between these counts and the pure luminosity evolution model; in the magnitude range $14 < H < 18$ we find a best fit normalisation of $1.095^{+0.035}_{-0.034}$, where 1.0 corresponds to the Metcalfe et al. (2005) normalisation shown in Fig. 8. Varying the fitting range does slightly alter the result; in the range $16 < H < 18$ we find a best fit normalisation of $1.061^{+0.048}_{-0.033}$ for example.

5 DISCUSSION

In the previous sections, bright H-band number counts from 2MASS were determined over the APM survey area (≈ 4000 deg^2) and almost the entire 66 per cent of the sky ($|b| > 20°$, ≈27 000 deg^2), along with faint counts to $H = 18$ over a combined solid angle of 0.69 deg^2 applying a zeropoint consistent with 2MASS. The bright H-band number counts over the APM survey area are extremely low (≈ 25 per cent at $H = 13$) with respect to homogeneous predictions, and reproduce the form of the bright counts observed in the optical B-band (Busswell et al. 2004) and the near infrared K_s-band (Frith et al. 2005a). Previous work has suggested that, if due solely to local large-scale structure, these low counts would be at odds with the form of clustering expected in a ΛCDM cosmology. In addition, the bright H-band $|b| > 20°$ counts were also found to be low. In the following section, various possible causes for these low counts are examined.

5.1 Model normalisation

The normalisation of number count models may be determined by fixing the predicted to the observed number of galaxies at faint magnitudes. The magnitude range at which this is done should be bright enough to avoid large uncertainties in the evolutionary model while faint enough such that

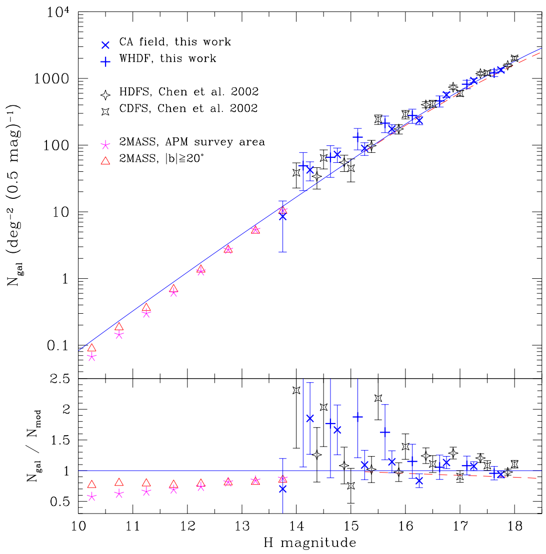

Figure 7. Here we show H-band galaxy number counts for the two separate fields observed in this work, the Calar Alto field (CA field; 0.27 deg^2) and the William Herschel Deep field (WHDF; 0.06 deg^2). We also show number counts determined for the two separate fields of the LCIRS (Chen et al. 2002) situated in the Hubble Deep Field South (HDFS; 0.24 deg^2) and Chandra Deep Field South (CDFS; 0.16 deg^2), subtracting 0.28 magnitudes in each case in order to bring the LCIRS and 2MASS zeropoints (and hence also the CA field and WHDF zeropoints) into agreement. We also show bright number counts extracted from 2MASS for the APM survey area and for $|b|$ >20° as shown in Fig. 3. The models are indicated as in Fig. 1. In the lower panel, we divide through by the pure luminosity evolution homogeneous prediction as in Figs. 3 and 4. At faint magnitudes, we indicate the Poisson uncertainty in each bin. We omit Poisson errors on the bright counts for clarity (see Fig. 4 for these). We discuss the uncertainty in the counts arising from cosmic variance in section 5.

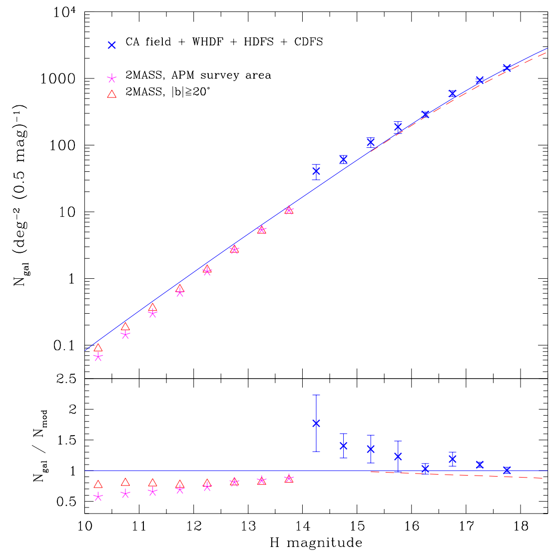

Figure 8. Here we show the faint H-band data from the two fields presented in this work (CA field and WHDF) and the two fields published by the LCIRS (HDFS and CDFS; Chen et al. 2002), applying a zeropoint to the LCIRS data consistent with the bright H-band 2MASS data (and hence the CA field and WHDF also), as shown in Fig. 7. The errorbars at faint magnitudes indicate the field-to-field error, weighted in order to account for the different solid angles of each field. Bright H-band counts extracted from 2MASS for the APM survey area and for $|b|$ >20° are shown as previously. In the lower panel, the counts are divided through by the pure luminosity evolution homogeneous prediction as before.

large fluctuations in the counts arising from cosmic variance are expected to be small. Near infrared wavelengths are expected to be insensitive to luminosity evolution at bright magnitudes, making the H-band particularly useful for such analysis. Of vital importance when determining the model normalisation is that when making comparisons between faint and bright counts, the zeropoints are consistent; an offset of a few tenths of a magnitude between the two, for example, would be enough to remove the observed anomaly in the bright counts over the APM survey area.

Applying the 2MASS zeropoint to the faint H-band data presented in this work and the LCIRS data (Chen et al. 2002), covering a combined solid angle of 0.69 deg^2, it is clear that a discrepancy between the bright and faint counts exists; the model normalisation used previously, which indicates low counts below $H = 14$ over the APM survey area (and for $|b|$ >20°), provides good agreement with the faint data. In fact, fixing the model to the faint counts implies a slightly higher normalisation. This agreement, as indicated by the errorbars in Fig. 8, suggests that the discrepancy between the bright and faint counts is not due to cosmic variance in the faint data. To remove the observed deficit in the APM survey area counts below $H = 14$ by renormalising the model, requires a deviation from the faint counts of 7.0σ using the best fit normalisation of $1.095^{+0.035}_{-0.034}$ (determined for $14 < H < 18$). Similarly, renormalising to the $|b|$ >20° counts would require a deviation of 7.2σ from the faint data.

In addition, the model normalisation may also be scrutinised through comparison with redshift distributions. Fig. 2 shows the Metcalfe et al. (2005) pure luminosity evolution model compared with H-band $n(z)$ determined through a match between 2MASS and the 2dFGRS Northern and Southern declination strips. The model predictions appear to be consistent with the observations, with relatively homogeneous distributions beyond $z = 0.1$ (1 per cent and 8 per cent over-dense in the North and South respectively). Lowering the model normalisation to fit the bright 2MASS number counts would compromise this agreement and imply large over-densities beyond $z = 0.1$ (19 per cent and 27 per cent in the North and South respectively).

5.2 Galaxy evolution

A change in amplitude therefore, cannot easily account for the discrepancy in the number counts at bright magnitudes. However, could an unexpected change in the slope of the number count model contribute? In section 2, we examined

the consistency of the number counts at bright magnitudes with the underlying redshift distribution, assuming a model with insignificant levels of luminosity evolution at low redshift. The predictions derived from the observed $n(z)$ were in good agreement with the observed number counts indicating that luminosity evolution at low redshift is unlikely to have a significant impact on the form of the counts at bright magnitudes. This is supported by the consistency of the pure luminosity evolution model with the observed redshift distributions (Fig. 2); strong low redshift luminosity evolution produces a tail in the $n(z)$ which would imply large deficiencies at high redshift.

Could unexpectedly high levels of luminosity evolution at higher redshifts affect our interpretation of the bright counts? If the slope of the homogeneous prediction were to increase significantly above $H \approx 14$ from the evolutionary models considered in this paper, then the model normalisation could effectively be lowered into agreement with the bright counts. The problem with this is that the number counts beyond $H \approx 14$ are consistent with low levels of luminosity evolution to extremely faint magnitudes ($H \approx 26$). Models with significantly higher levels of luminosity evolution above $H \approx 14$ would therefore compromise this agreement.

Therefore, it appears that relatively low levels of luminosity evolution are consistent with number count observations to high redshifts. Also, recent evidence from the COMBO-17 survey, examining the evolution of early-type galaxies using nearly 5000 objects to $z \approx 1$ (Bell et al. 2004), suggests that density evolution will also not contribute; ϕ^* appears to decrease with redshift indicating that the number of objects on the red sequence increases with time, and so acts contrary to the low counts observed at bright magnitudes. This picture is supported by the K20 survey (Cimatti et al. 2002), which includes redshifts for 480 galaxies to a mean depth of $\bar{z} \approx 0.7$ and a magnitude limit of $K_s = 20$ with high completeness. The resulting redshift distribution is consistent with low levels of luminosity and density evolution (Metcalfe et al. 2005).

In summary, significant levels of evolution are not expected in passive or star forming pure luminosity evolution models, although could occur through dynamical evolution. However, the pure luinosity evolution models of Metcalfe et al. (2005) fit the observed $H < 14$ $n(z)$ at $z > 0.1$; it is at lower redshifts that there are fluctuations. In addition, these models continue to fit the observed $n(z)$ at very high redshift and the number counts to extremely faint magnitudes ($K \approx 23$), suggesting that there is little need for evolution at $z \approx 1$, far less $z \lesssim 0.1$. Some combination of dynamical and luminosity evolution might be able to account for these observations; however it would require fine-tuning in order to fit both the steep counts at bright magnitudes and the unevolved $n(z)$ at low and high redshifts.

5.3 Photometry issues & completeness

The number counts shown in Figs. 7 and 8 show bright and faint counts with a consistent zeropoint applied. Photometry comparisons have been made using several hundred point sources matched at bright magnitudes. In order to check that the applied zeropoints are consistent with the *galaxy* samples, we also compare the 2MASS photometry with 24 matched galaxies in the CA field and WHDF and 16 in the LCIRS samples; we find that the mean offsets are -0.01 ± 0.04 and -0.32 ± 0.06, consistent with the zeropoints determined via the 2MASS point sources. The comparisons with the 2MASS point source catalogue (Figs. 5 and 6) also indicate that there is no evidence of scale error in either of the faint samples to $H \approx 16$.

Could the discrepancy between the bright and faint counts arise from an under-estimation of the total flux of the galaxies? Recall that we make no correction to total magnitude for the faint data presented in this work; however, under-estimating the total flux in the faint data would only increase the observed deficit in the counts at bright magnitudes, if the model normalisation is adjusted to fit the faint counts. The good agreement between the point source and galaxy zeropoints suggests that the estimate for the total galaxy flux is comparable in the bright and faint data. At bright magnitudes, the 2MASS extrapolated H-band magnitudes are used. In the K_s-band, this magnitude estimator has been shown to be an excellent estimate of the total flux, through comparisons with the total K_s-band magnitude estimator of Jones et al. (2004) and the K-band photometry of Loveday (2000).

Another possible contribution to the low counts could be high levels of incompleteness in the 2MASS survey. As with the possible systematic effects described previously, it is differing levels of completeness in the faint and bright data which would be important. The 2MASS literature quotes the extended source catalogue completeness as > 90 per cent (see the 2MASS website for example). Independently, Bell et al. (2003) suggest that the level of completeness is high ($\approx$99 per cent), determined via comparisons with the SDSS Early Data Release spectroscopic data and the 2dFGRS. The faint data presented in this work and the LCIRS data are likely to suffer less from incompleteness, as we cut well below the magnitude limit, are subject to lower levels of stellar confusion and suffer less from low resolution effects. Incompleteness in 2MASS will therefore affect the observed deficit in the bright counts at the < 10 per cent level, although the effect is likely to be at the low end of this constraint due to incompleteness in the faint catalogues and suggestions that the 2MASS extended source catalogue is fairly complete.

5.4 Large-scale structure

It appears therefore, that the observed deficiency in the bright counts might be significantly affected by incompleteness in the 2MASS extended source catalogue. However, the level to which other systematic effects such as the model normalisation, luminosity evolution and photometry issues appears to be small. The question then is – accounting for these various sources of error or uncertainty, are the deficiencies in the bright H-band counts over the APM survey area and for $|b| > 20^\circ$ still at odds with the expected fluctuations in the counts arising from local large-scale structure in a ΛCDM cosmology, as suggested in previous work (Busswell et al. 2004; Frith et al. 2005a)?

We determine the expected fluctuations in the bright number counts due to cosmic variance via ΛCDM mock 2MASS catalogues; these are described in detail in Frith et al. (2005a). To recap, we apply the 2MASS selec-

tion function to 27 virtually independent volumes of $r = 500\,h^{-1}$ Mpc formed from the $3000^3 h^{-3}$Mpc^3 ΛCDM Hubble Volume simulation. This simulation has input parameters of $\Omega_m = 0.3$, $\Omega_b = 0.04$, $h = 0.7$ and $\sigma_8 = 0.9$ (Jenkins et al. 1998). The mean number density of the counts at the magnitude limit is set to that of the observed 2MASS density.

We are now in a position to estimate the significance of the observed bright H-band counts. We use the 1σ fluctuation in the counts expected in a ΛCDM cosmology (determined using the 2MASS mocks described above), which for the APM survey area is 7.63 per cent (for $H < 13$) and 4.79 per cent (for $H < 14$), and for $|b| > 20^\circ$ is 3.25 per cent (for $H < 13$) and 1.90 per cent (for $H < 14$). In addition we also take into account the uncertainty in the model normalisation; we use the best fit normalisation of the Metcalfe et al. (2005) pure luminosity evolution model (a factor of 1.095 above the Metcalfe et al. (2005) model) and add the uncertainty of ± 3.1 per cent derived from the faint H-band counts (presented in Fig. 8) in quadrature. Regarding the possible effect arising from survey incompleteness, we first assume that the level of incompleteness is comparable in the faint and bright data; the resulting significance for the APM survey area and $|b| > 20^\circ$ bright counts are shown in column 3 of table 2. This represents an upper limit on the significance since we have effectively assumed that there is no difference in the incompleteness between the bright and faint datasets. In column 4 of table 2, we assume that there is a difference in the completeness levels in the faint and bright data of 10 per cent. This represents a lower limit on the significance (assuming that there are no further significant systematic effects), since we assume that the completeness of the 2MASS extended source catalogue is 90 per cent (the lower limit) and that there is no incompleteness in the faint data.

Therefore, assuming a ΛCDM cosmology, it appears that the observed counts over the APM survey area might be in line with a rare fluctuation in the local galaxy distribution. However, the counts over 66 per cent of the sky ($|b| > 20^\circ$) suggest a deficiency in the counts that are at odds with ΛCDM, even accounting for a 10 per cent incompleteness effect and the measured uncertainty in the best fit model normalisation.

Field	H_{lim}	Significance (no incompleteness correction)	Significance (assuming 10 per cent incompleteness)
APM	13.0	3.7σ	2.5σ
APM	14.0	4.2σ	2.4σ
$\lvert b\rvert > 20^\circ$	13.0	6.1σ	3.8σ
$\lvert b\rvert > 20^\circ$	14.0	6.8σ	4.0σ

Table 2. Here we show the significance of the H-band 2MASS counts extracted for the $\approx$4000 deg^2 APM survey area and for $|b| > 20^\circ$, for $H < 13$ and $H < 14$. In each case we determine the expected cosmic variance using a ΛCDM form to the large-scale power determined via mocks constructed from the Hubble Volume simulation. In addition we use the best fit normalisation of the Metcalfe et al. (2005) pure luminosity evolution model determined at faint magnitudes (a factor of 1.095 above the original normalisation) and add the uncertainty on this (± 3.1 per cent) in quadrature to the expected cosmic variance. In the third column we use the observed counts as shown in Figs. 4, 7 and 8; in the fourth column we account for an upper limit on the incompleteness in the 2MASS extended source catalogue of 10 per cent; the level to which this will affect the significance is likely to be lower due to incompleteness in the faint data.

6 CONCLUSIONS

We have presented new H-band photometry over two fields with a combined solid angle of 0.30 deg^2 to $H \approx 19$. The zeropoint is chosen to match that of the 2MASS photometry at the bright end and is accurate to ± 0.01 magnitudes. In addition we have examined the faint H-band data of the LCIRS (Chen et al. 2002) which covers two fields with a combined solid angle of 0.39 deg^2 to $H \approx 20$. The zeropoint of this data appears to be offset from the 2MASS photometry by 0.28 ± 0.01 magnitudes. Applying a consistent zeropoint, the faint counts determined from the new data presented in this work and the LCIRS are in good agreement with the pure luminosity evolution model of Metcalfe et al. (2005), with a best fit normalisation a factor of $1.095^{+0.035}_{-0.034}$ higher.

In contrast, the bright H-band counts extracted from 2MASS over the $\approx$4000 deg^2 APM survey area around the southern galactic pole are low with respect to this model, corroborating previous results over this area in the optical B-band and near infrared K_s-band (Busswell et al. 2004; Frith et al. 2005a). In addition, the counts extracted for almost the entire survey, covering 66 per cent of ths sky, are also low with a deficit of $15 - 20$ per cent to $H = 14$. Importantly, this discrepancy does not appear to be due to zeropoint differences between the faint and bright data or uncertainty in the model normalisation set by the faint counts.

We have investigated various possible sources of systematic error which might affect this result: The counts are consistent with low levels of luminosity and density evolution, as predicted by the pure luminosity evolution model of Metcalfe et al. (2005), to extremely faint magnitudes (see Fig. 1). Also, the photometry appears to be consistent between the faint and bright *galaxy* data using a zeropoint applied via comparisons between point sources. However, differing incompleteness in the bright and faint galaxy samples might have a significant impact; completeness in the 2MASS extended source catalogue is > 90 per cent.

Finally, we determined the expected cosmic variance in the bright number counts from ΛCDM mock 2MASS catalogues. Allowing for the model normalisation uncertainty determined from the faint counts, and using an upper limit on the incompleteness in the 2MASS galaxy sample, the deficiency in the counts over the APM survey area represent a rare ($\approx$1 in 100) fluctuation in a ΛCDM cosmology. However, the low H-band counts for $|b| > 20^\circ$ suggest that this deficiency might extend over the entire local galaxy distribution; allowing for incompleteness and the model normalisation uncertainty as before, this would represent a 4σ fluctuation (<1 in 10 000) in the local galaxy distribution, and would therefore be at odds with the expected form of clustering expected in a ΛCDM cosmology on large scales. The increase in faint near infrared data from the UK Infrared Deep Sky Survey (UKIDSS) should help to resolve this issue.

ACKNOWLEDGEMENTS

The new data presented in this paper were based on observations collected at the Centro Astronòmico Hispano Alemán (CAHA) at Calar Alto, operated jointly by the Max-Planck Institut für Astronomie and the Instituto de Astrofíca de Andalucía (CISC). This publication also makes use of data products from the 2 Micron All-Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Centre/California Institute of Technology, funded by the Aeronautics and Space Administration and the National Science Foundation. We thank Peter Draper for his help with Sextractor. We also thank the wonderful Phil Outram and John Lucey for useful discussion and Nicholas Ross for assistance with the Calar Alto field selection.

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